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The Center-TRACON Automation System: Simulation and Field Testing

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The Center-TRACON Automation System: Simulation and Field Testing

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Summary

A new concept for air traffic management in the terminal area, implemented as the Center-TRACON Automation System, has been under development at NASA Ames in a cooperative program with the FAA since 1991. The development has been strongly influenced by concurrent simulation and field site evaluations. The role of simulation and field activities in the development process will be discussed. Results of recent simulation and field tests will be presented.

Introduction

A system for the automated management and control of terminal area traffic to improve productivity, referred to as the Center-TRACON Automation System (CTAS), is being developed at NASA Ames Research Center under a joint program with the FAA (ref. 1). CTAS consists of three types of integrated tools that provide computer-generated advisories for both en-route and terminal area controllers to manage and control arrival traffic efficiently. The first tool, the Traffic Management Advisor (TMA), generates runway assignments, landing sequences, and landing times for all arriving aircraft, including those originating from nearby feeder airports (ref. 2). TMA also assists in runway configuration control and flow management. The second tool, the Descent Advisor (DA), generates clearances for the en-route controllers handling arrival flows to metering gates (ref. 3). The DA's clearances ensure fuel-efficient and conflict free descents to the metering gates at specified crossing times. The third tool, the Final Approach Spacing Tool (FAST) provides terminal area controllers with heading and speed advisories to help produce an accurately spaced flow of aircraft onto the final approach course (ref. 4).

The underlying premise behind the design of CTAS has been that successful planning of traffic in capacity constrained airspace requires the ability to accurately predict future traffic situations. The technology for accurate prediction of trajectories was developed in the early 1970s and has been incorporated in modern flight management systems. Data bases consisting of several hundred aircraft performance models, airline preferred operational procedures and a three dimensional wind model support the trajectory prediction capabilities within CTAS. (This is discussed in ref. 7.)

The primary research effort within CTAS has been the design of a set of automation tools that make use of this trajectory prediction capability to assist the controller in overall management of traffic. The two criteria upon which success is judged are controller acceptance and improvement in traffic flow as measured by reduced delays and improved aircraft operating efficiencies. Because of the complexity of the air space system, the approach taken has been to adopt a "design a little, test a lot" philosophy with real-time simulation and field testing included as an integral part of the design process. Analysis of real-time data and fast-time simulation methods are used to extrapolate the results of the field tests.

The purpose of this paper is to review the process used in the development of CTAS and provide examples of the role of real-time simulation, field testing, and fast-time simulation. The paper will first discuss the overall technical approach. To illustrate the approach, the FAST development will be reviewed. The DA tool is somewhat different from FAST in that it allows more strategic control. This has led to some differences in the DA development approach that will be discussed.

Technical Approach

The overall technical approach is shown in figure 1. Instead of following the more traditional sequential-approach, the requirements, design, simulation, and operational tests are conducted concurrently with a high level of interaction. Analysis of real-time simulation and live traffic data are used with fast-time simulation to quantify and extrapolate the performance of the system. A primary advantage of this approach is the involvement of controllers and pilots throughout the development.

The research facility established to support this approach is illustrated in figure 2. The primary ATC simulation was developed at Ames. It includes an air traffic simulation using pseudo-pilots and an ATC facility simulation. Both are hosted on a network of workstations. To study controller display integration issues, two terminal area radar displays (Fully Digital ARTS Display System,

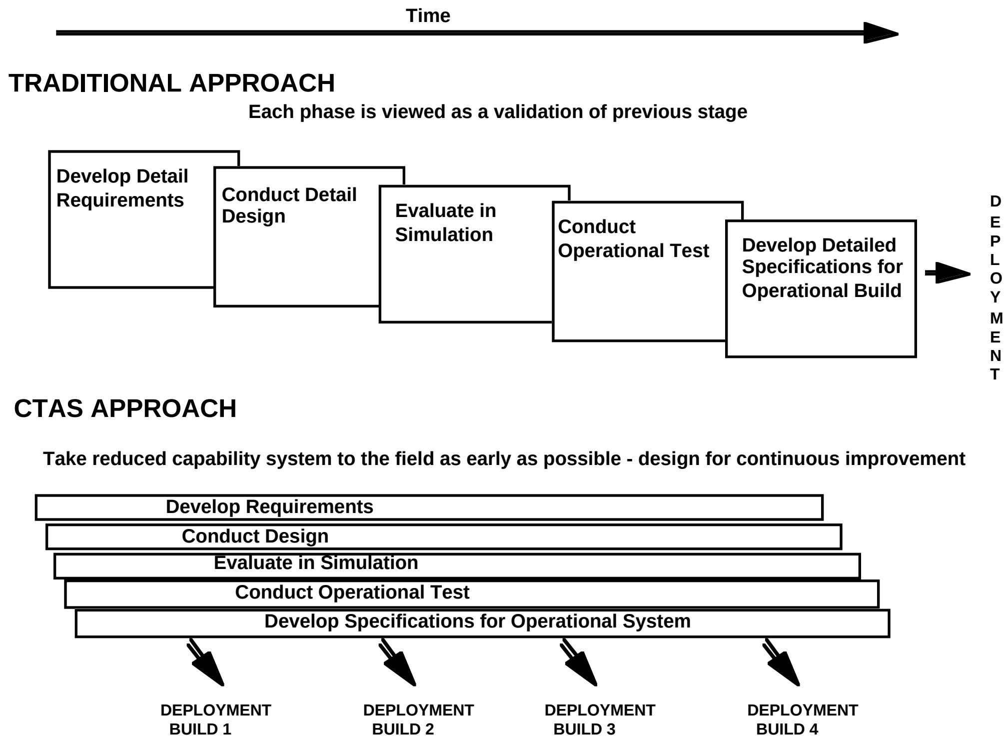


Figure 1. Programmatic approach.

FDADS) are integrated into the network. To investigate specific air-ground communication and traffic management issues, links were established with existing full piloted simulators located at the Ames and Langley Research Centers. To understand actual traffic situations and to support shadowing evaluations, live radar connections were established, first with Denver Center and then expanded to include the Fort Worth Center and the Dallas/Fort Worth terminal area (TRACON). To understand weather and evaluate its effect on the trajectory prediction capability of CTAS, connections were established to receive weather information for both the Denver and Dallas/Fort Worth areas. We are currently receiving "rapid update cycle" weather data. Field tests are under way at Denver and Dallas.

Application to Development of FAST

The steps taken in the FAST development are illustrated in figure 3. Fast-time simulation, real-time simulation, and live traffic testing in shadow-mode have been used throughout the development (ref. 5). Operational testing has been maintained as a target but has been delayed until the system design issues identified in simulation and shadow-mode testing are resolved. Controllers have been involved throughout the process. Initial studies considered a generic airspace designed to evaluate basic concepts. As the program progressed, the effort addressed more realistic environments based on the Denver and Dallas/Fort Worth areas.

FAST Description

FAST is a tool for aiding the terminal area controller in setting up the optimal landing sequence, selecting the most appropriate runway and providing the controller with turn and speed advisories to produce an accurately spaced flow of aircraft onto the final approach course (ref. 4). The sequence and runway advisors are referred to as "passive FAST." The turn and speed advisories are referred to as "active FAST." Both passive and active FAST advisories are based on trajectories that have been computed to be conflict free for the duration of the flight path. These trajectories and advisories are continually updated based on new radar track data (every 4.7 seconds) and on inference of controller intent. More details on FAST are contained in references 4 and 6. The trajectory prediction computations are reviewed in reference 7.

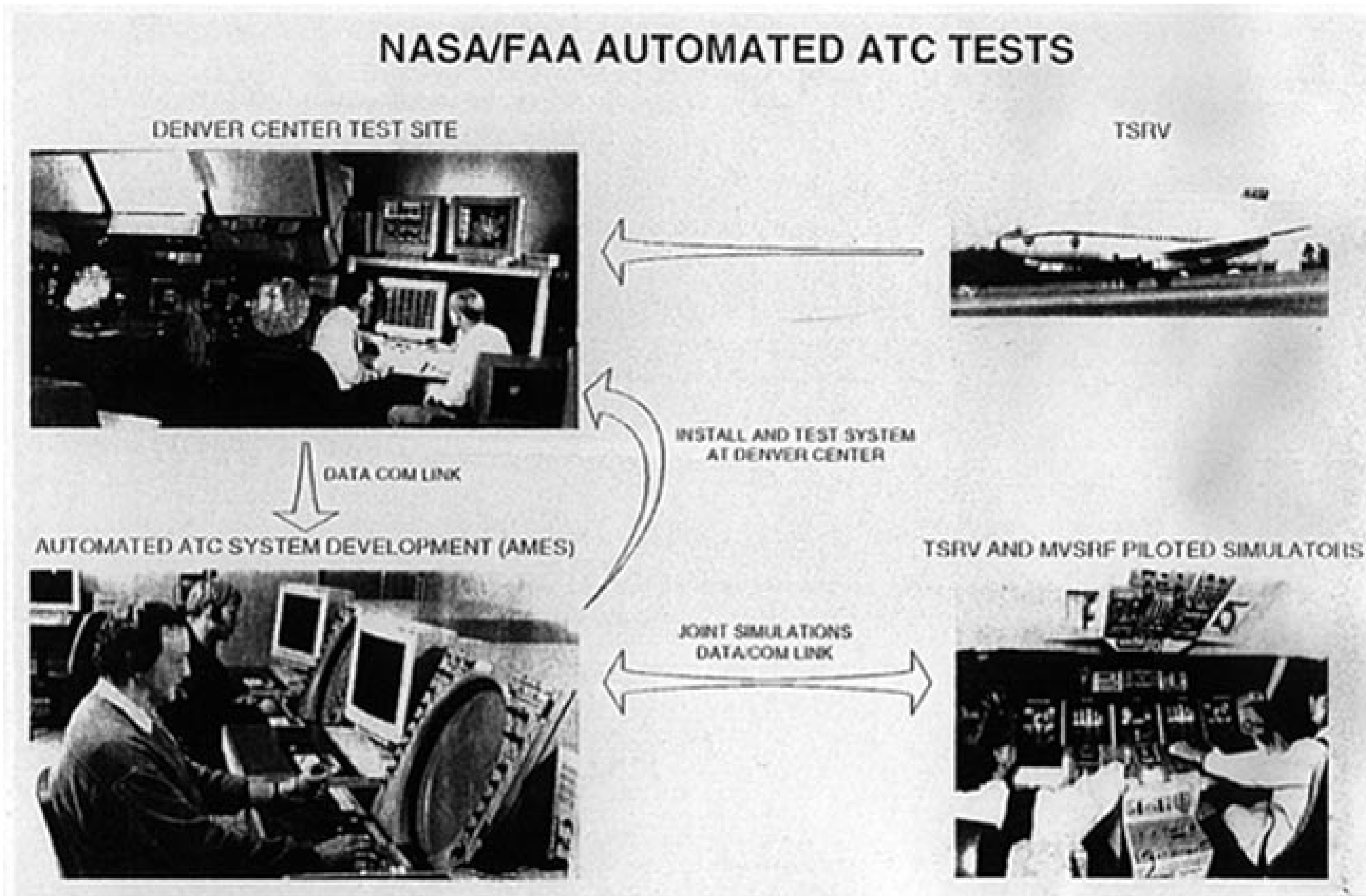


Figure 2. Research facility.

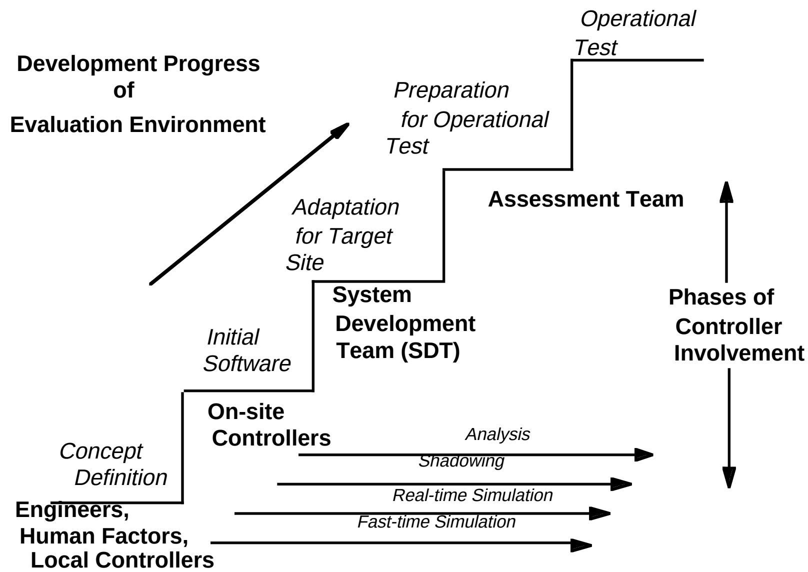


Figure 3. FAST development process.

As an example of the development process, we will review the developments of the sequence and scheduling logic and the runway allocation logic.

Sequencing and Scheduling Algorithm

The sequencing and scheduling problem addressed within FAST are illustrated in figure 4. In the initial design, the sequence and schedule were optimized to assure minimum delays based on separations at the threshold. The speed and turn advisories were computed to assure efficient and conflict free flight (ref. 8). To achieve minimum delays, the system would allow overtakes upstream in the traffic flow. As the simulation was adapted to be more representative of Denver and Dallas/Fort Worth, it became apparent that additional sequence constraints would be required to allow the controller to maintain a coherent view of the traffic situation. This led to the development of a trajectory segment based ordering logic that under certain conditions would maintain sequences established prior to merging on final (refs. 4 and 6). The segment based ordering method allows the overtake of one aircraft by another if there is a sufficient reduction in delay but it restricts the conditions under which this reordering may occur. The logic for the reordering was derived from over 2000 hours of real-time simulations involving controllers from Dallas/Fort Worth. It is imbedded in the CTAS code in the form of fuzzy logic. An example of the resulting logic for a reordering is shown in figure 5. Without going into the details, the logic for determining whether to allow an overtake depends on the relative position of two aircraft scheduled for the same segment in the TRACON (i.e., downwind, final, etc.), their speed differences, and the potential delay savings. If the trailing aircraft falls above the curve in figure 5, it is rescheduled. Subsequent analysis and fast-time simulation have shown that these additional constraints impose a negligible penalty on overall performance.

Runway Allocation

The runway allocation algorithm has evolved from an initial algorithm that was designed to optimize a single functional (ref. 9), to an algorithm that is more consistent with current procedures, provides improved controller awareness, and allows consideration of multiple performance metrics (refs. 4 and 6). The current method begins with a nominal runway assignment based on published procedures at the particular airport. A decision tree is entered which branches through alternative runways, entry gate to the TRACON, aircraft type, and finally ends with a minimum global delay reduction required for a runway change. The overall benefit due to a runway change is computed and compared with the predetermined minimum delay reduction. If the delay reduction exceeds the minimum delay, the change is made.

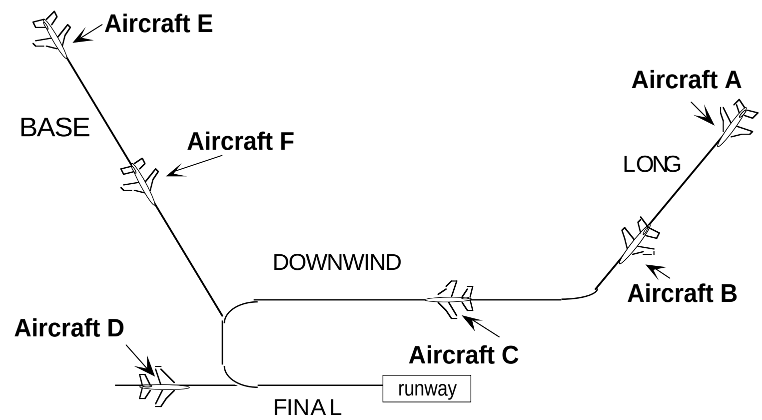


Figure 4. FAST sequencing and scheduling.

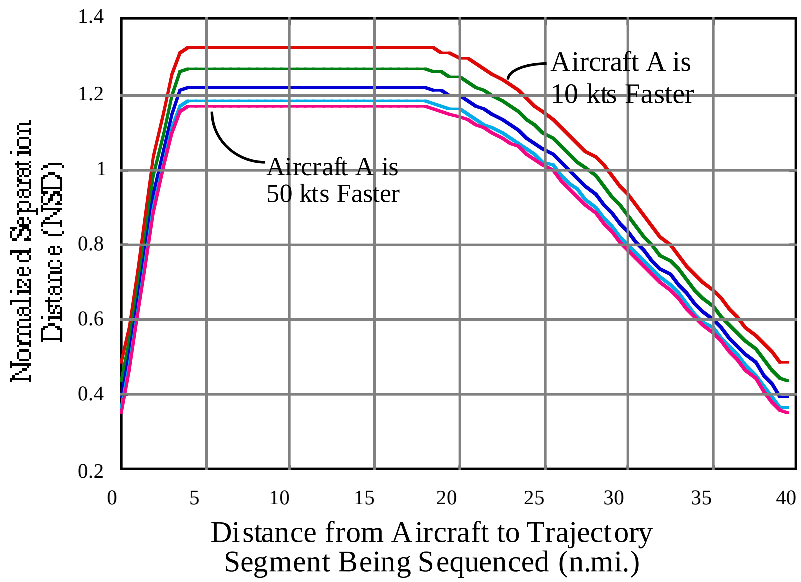


Figure 5. Knowledge based sequencing decision curves.

Real-time simulation and shadow mode operation have demonstrated the value of the runway allocation algorithm in two areas. The most significant improvement has been in elevating the performance of all controller crews to that of the best controller crews. Based on real-time analysis, to be discussed later, there is a large variation in the utilization of multiple runways as a function of different controller teams. A second area of improvement, even for the better controller teams, has been the identification of runway changes based on traffic information not available to the specific sector controller. This is illustrated in figure 6. The arrival sector controller may not be aware of the additional traffic coming in on the upper right side and as a result assign the aircraft on the lower right to the left runway. Due to a more global awareness of traffic, FAST would be able to determine an advantage in switching the aircraft to the right runway.

Human Factors Assessments

The CTAS development has incorporated the expertise of the end-user from the very beginning. The design has been guided by the premise that automation should extend a controller's ability to manage traffic rather than change a controller's overall responsibilities.

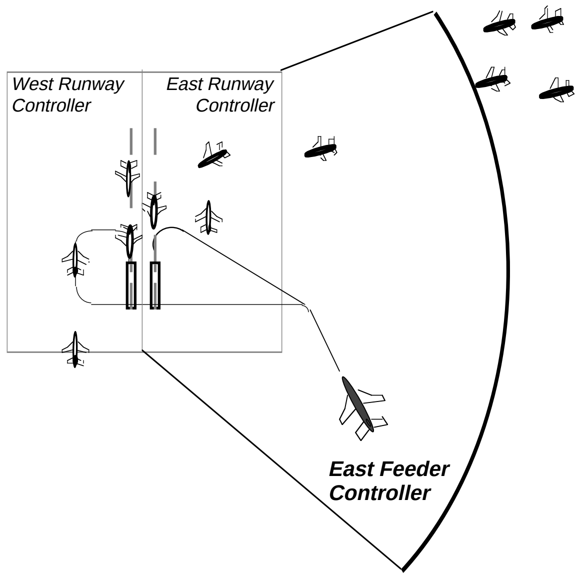


Figure 6. Knowledge based runway allocation.

To maintain this focus, a human factors team was assembled by the FAA Liaison Office at Ames to work directly with the engineering staff. Additionally, the FAA established a team of experienced and highly skilled controllers to work with the team. Controller acceptance has been evaluated through observation, conducting interviews, recording the number of communications, and taking controller evaluations using various rating scales. In an attempt to standardize controller ratings a "Controller Acceptance Rating Scale (CARS)," is being developed (ref. 5). An early version of the CARS is shown in figure 7. The idea is borrowed from the "Cooper Harper Rating" that has been very successful in standardizing pilot ratings for aircraft handling qualities (ref. 10).

Analysis of Real-Time Data

So far, we have been discussing the development process. To understand whether the concept will provide benefit, techniques for analyzing real-time data are required to assure that the system will perform as expected in the real-world and to assist in quantifying potential benefits through use with fast-time simulation.

The real-time analysis conducted in support of CTAS is to be published this fall in an article by M. Ballin and H. Erzberger (ref. 11). Two examples of this analysis are included here. First is the method used to calculate the arrival time errors at the feeder-fix into the terminal area. Based on fast-time simulation, Erzberger and Neuman have shown that the magnitude of these errors directly affect the portion of total delay that should be absorbed in the terminal area or TRACON (refs. 12 and 13). The second is the method used to measure inter-arrival spacing at the threshold for different aircraft combinations, i.e. heavy followed by heavy, large followed by small, etc. These data are necessary to understand the delay reduction potential of improved sequencing and spacing and runway assignment.

Figure 8 shows a composite plot of flights into DFW taken over a 140 minute interval involving a major rush. A program has been developed to assist developers in analyzing these data (ref. 14). The analysis program is constructed so that the CTAS estimated time of arrival (ETA) at the feeder fix, computed at any point along the trajectory, can be compared with the actual crossing time. The program is further refined so that a researcher can call up a specific trajectory to identify possible causes of any major error in the ETA. This tool has been invaluable in improving the overall robustness of the trajectory prediction algorithms.

An example of the use of this tool for obtaining statistical data on ETA errors is shown in figure 9. It should be noted that the curve appears to be the superposition of two error sources, one with a Gaussian distribution and one with a Poisson distribution. If the Gaussian portion is attributed to errors in the ETA calculations where the flight is not affected by controller-induced delays and the Poisson portion is attributed to delays inserted to coordinate traffic flow, we can make a first order estimate of ETA accuracy achievable with an effective traffic management tool.

Figure 10 shows a composite plot of flights into the terminal area. Here it is much more difficult to automatically sort through the data to achieve meaningful statistical results regarding ETA's at the threshold or estimates of the inter-arrival spacing. The tool must ignore all aircraft that are not landing, and it must identify the most likely runway for each landing aircraft. The greater the number of mistakes, the less valid the analysis.

Shown in figure 11 is an example histogram of inter-arrival spacing for aircraft having a legal separation of 2.5 n. mi. The few cases where separations were less than 2.5 n. mi. do not imply violations. Under current rules, as soon as the pilot has the runway in view, the pilot can declare VFR. Again, the curve seems to be a superposition of a Gaussian and Poisson distribution. In this case, it is assumed that the Gaussian portion represents the controller precision in spacing aircraft onto the final approach path given a steady stream of traffic and the Poisson portion represents those pairs where there were natural gaps. From these data, we can infer the controller target point, the errors that can be expected about the target point, and the buffer that can be used to model the controller's behavior. The potential for improvement

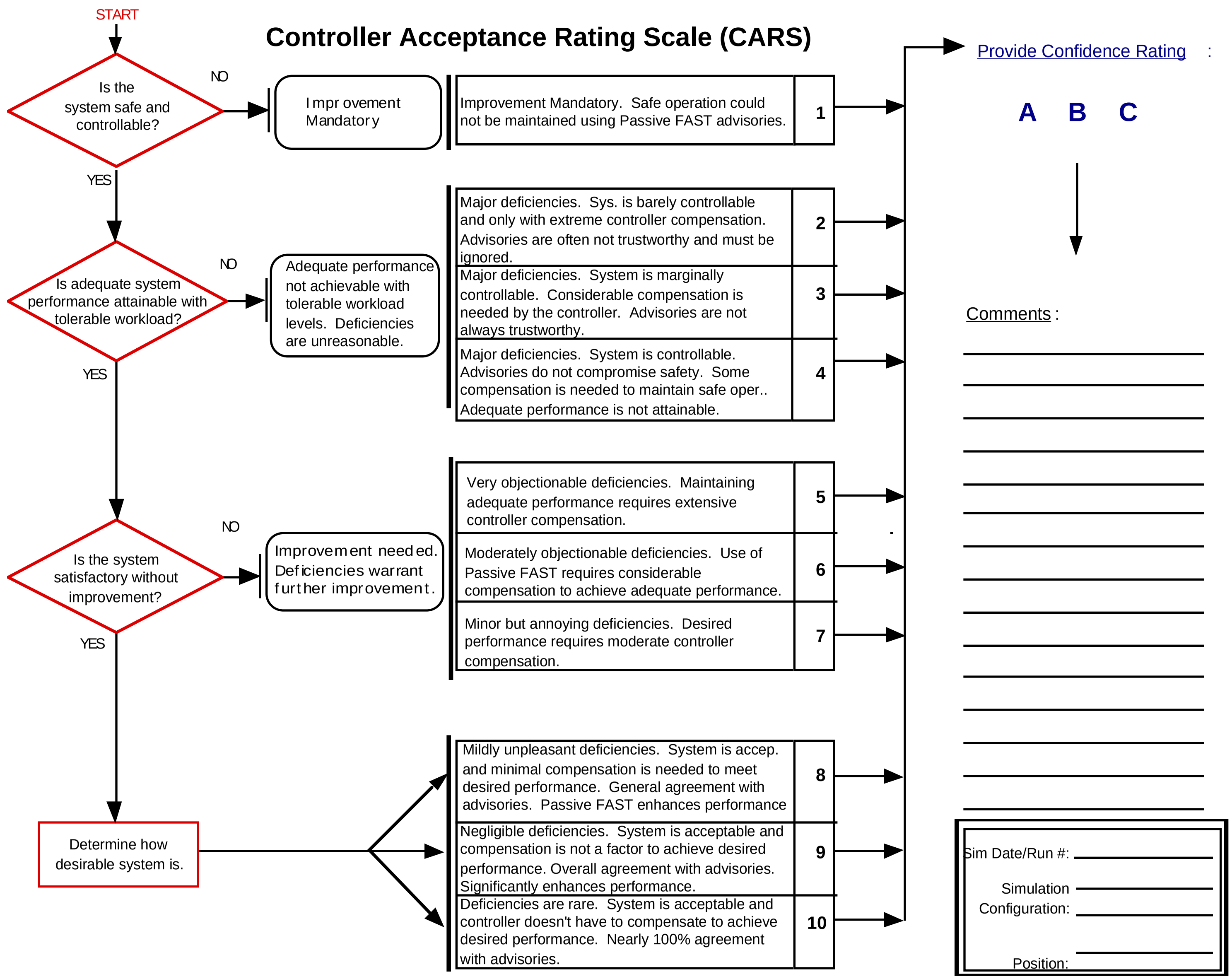


Figure 7. Controller acceptance rating.

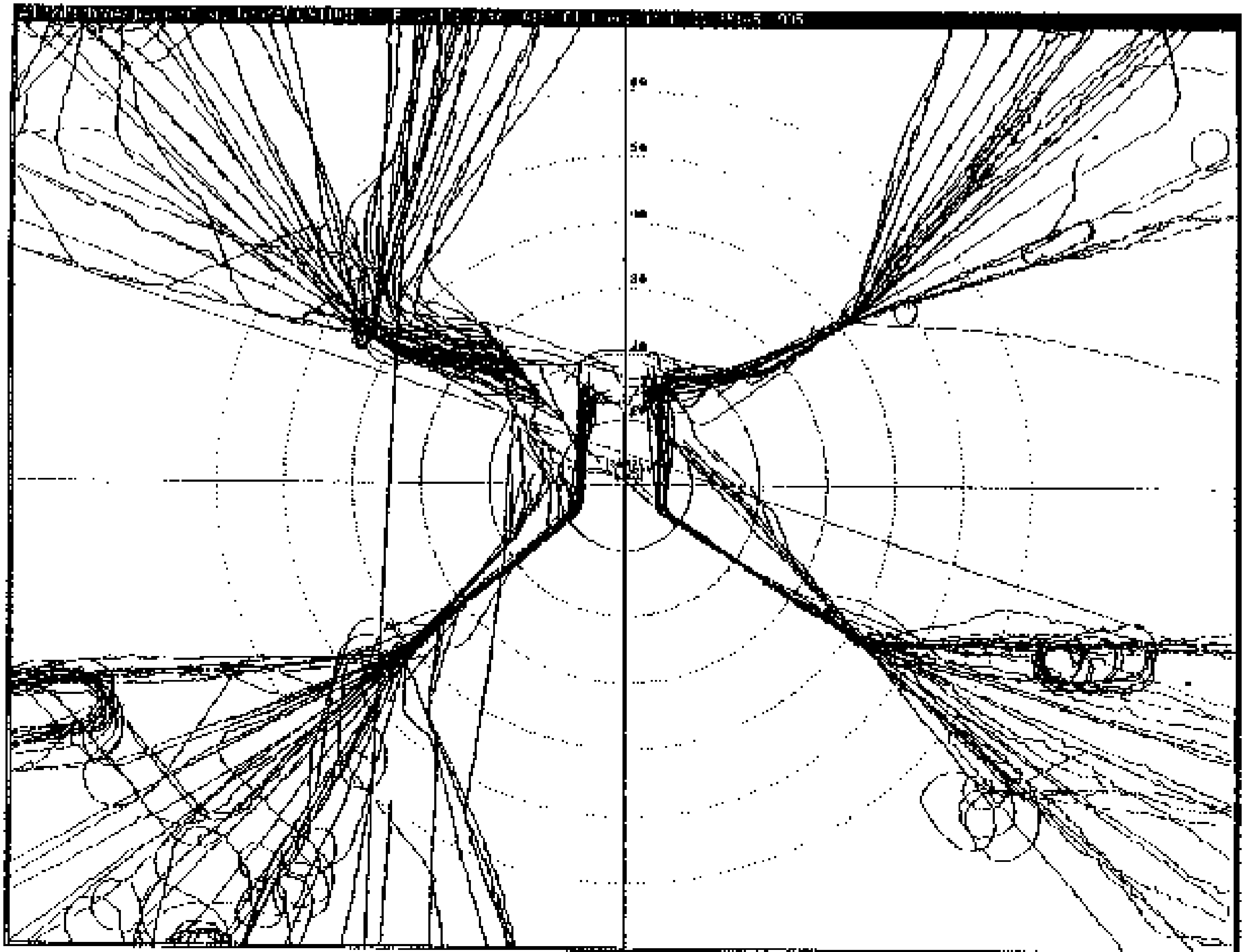

Radar tracks of arriving aircraft in the Center serving DFW.

Figure 8. Composite of Center flights feeding DFW.

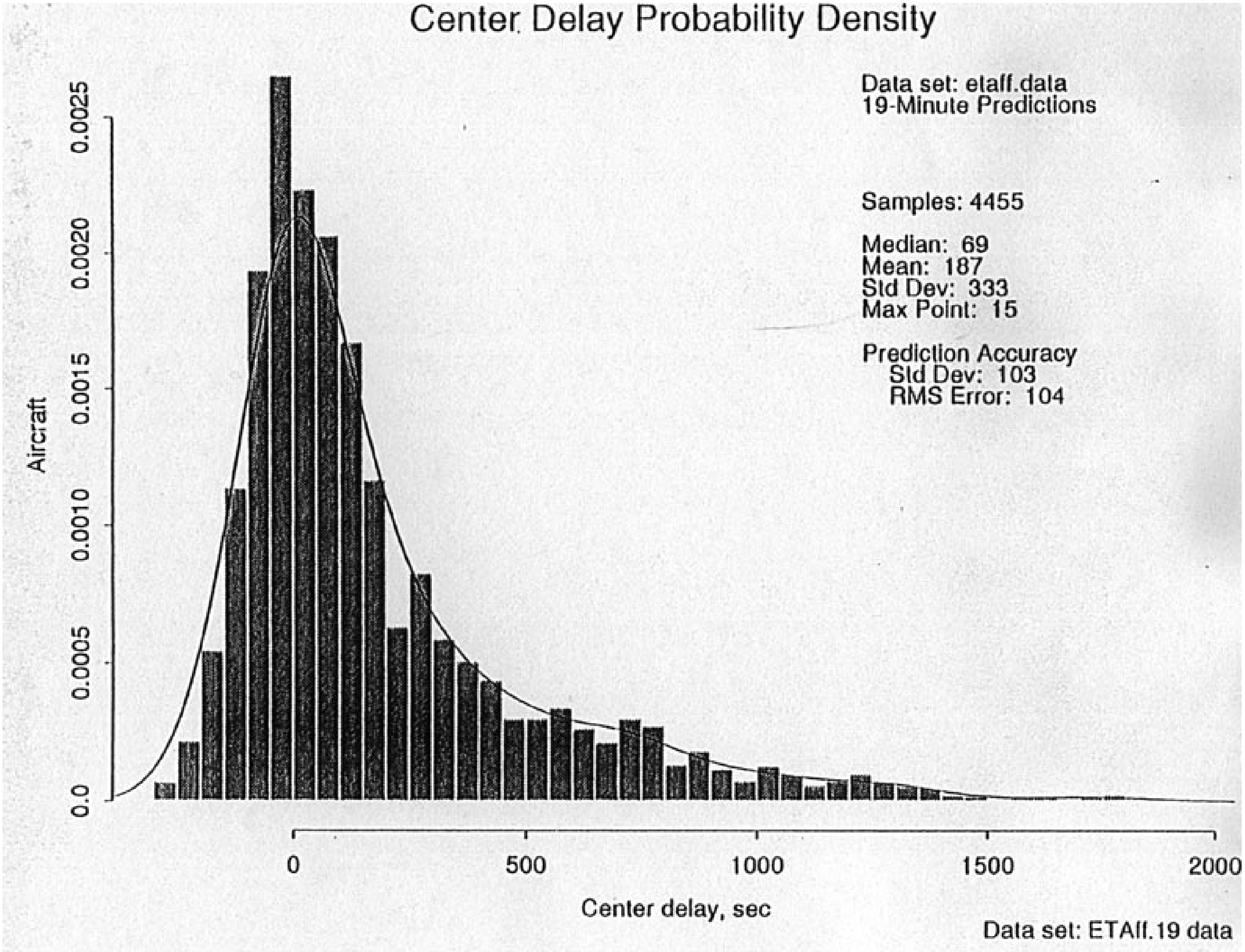
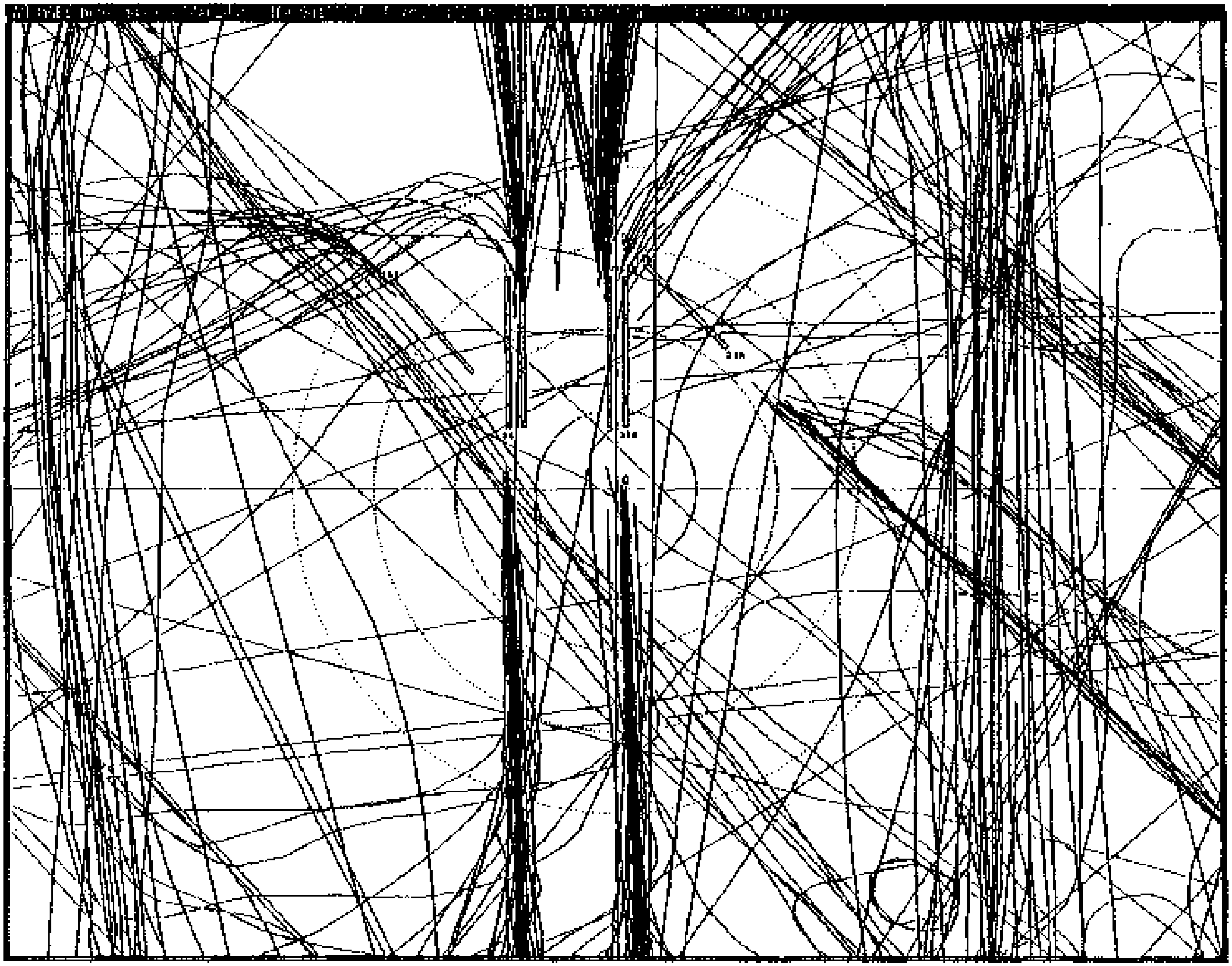


Figure 9. Histogram of ETA errors at meter fix.



Example of radar tracks during good meteorological conditions.

Figure 10. Composite of arrival flights.

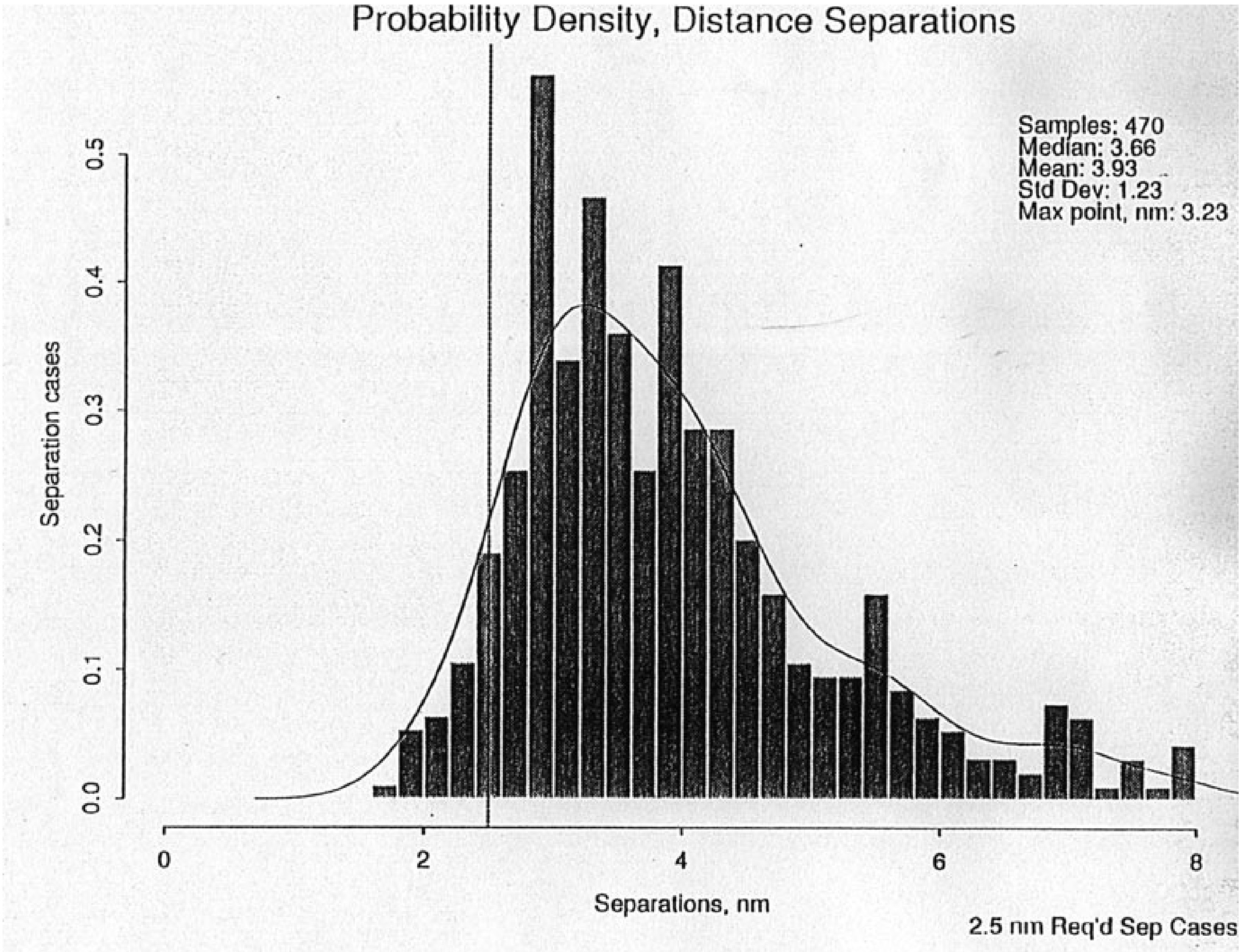


Figure 11. Histogram of interarrival spacing pairs requiring a 2.5 n. mi. separation.

is computed based on the expectation of achieving a reduced variance and buffer through the use of FAST advisories and the elimination of unnecessary gaps by improved runway balancing and delivery of aircraft into the terminal area.

Fast-Time Simulation

In contrast to real-time simulations, fast-time simulations permit examining the outcomes for many traffic periods with the same statistical parameters (ref. 12).

To facilitate fast-time simulation, a statistical model of the arrival traffic flow, a model of the runway and feeder fix configuration, and a model of the scheduler and automation tools must be developed. For these tests, the model is based on DFW using two runways. The traffic flow model is made up of four uniform distributions of traffic entering via the feeder fixes into the terminal area and scaled to represent a typical rush. The resulting traffic flows appear very similar to those observed at DFW. The traffic model can be scaled to represent different levels of traffic, tailored to represent different densities at individual gates, and constructed to be composed of specified percentages of aircraft types. The air traffic control model includes a set of simplifying assumptions. The simplifications include the use of fixed time based separation constraints at the threshold and meter fix, constant times for an aircraft to fly between the feeder-fix and the runway as a function of gate, as a function of runway assignment and aircraft type. It also assumes a fixed penalty in traversal time for a runway change. Accuracy's associated with meter-fix crossing times and inter-arrival spacing can be adjusted to understand the benefits that are achievable with different levels of automation.

A summary of the types of results that are computed using the simulation is shown in figure 12. Shown is the expected delay reduction as a function of arrival rate for different levels of automation. The baseline represents a traffic flow that is equally balanced between the two runways. The curve labeled knowledge based runway allocation, KBRA, shows the improvement achievable by allowing switches to the runway assignment to even out irregularities in the prearranged flow to the two runways. Similarly, the curve labeled "Active FAST" shows the further improvement due to more precise control of spacing on final. In recent studies, Erzberger and Neuman have used fast-time simulation to study the effect of errors in the meter-fix crossing time on (1) total delay and (2) the allocation of total delay between the Center and the terminal area (TRACON). The basic idea is that in the absence of uncertainty in the meter fix crossing time, none of the delay should be taken in the TRACON due to increased fuel burn rate at low altitudes. However, as errors are introduced into the meter-fix crossing time, if some delay is not allocated to the TRACON there may be a missed landing opportunity or at least an unnecessarily

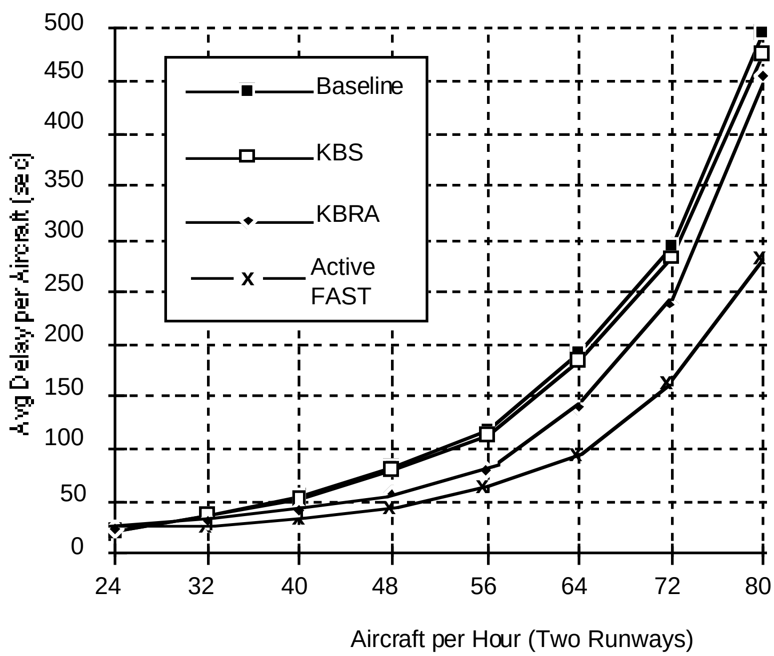


Figure 12. Delay reduction potential of CTAS.

large gap in the arrivals. This will result in larger total delays and increased total cost. This study will be presented as a subject of an AGARD lecture series to be presented by Dr. Erzberger later this year (ref. 13).

Differences in Development Approach Applied to DA

Although the DA development has been very similar to that taken in FAST, there are some fundamental differences. The major difference is that DA attempts to develop strategic clearances requiring few changes during the descent. This places a more stringent requirement on the trajectory prediction accuracy and has led to (1) the inclusion of pilots as well as controllers throughout the development process and (2) the conduction of limited field evaluations at an FAA facility during the early phases of development to validate procedures and trajectory prediction accuracy.

DA Description

The Descent Advisor is a set of automation tools to assist the controller in delivering aircraft to the meter fix at a specified time and with specified crossing restrictions in a manner consistent with preferences of the aircraft operator. The advisories are computed to be consistent with the specific aircraft performance and on-board equipment (flight management system, FMS, or non-FMS) and computed to be conflict free for the duration of the trajectory. The advisories are refreshed based on continuous analysis of new radar data and detection of non-conformance to clearances. The advisories include cruise Mach number, descent speed profile, top of descent for non-FMS equipped aircraft, path stretching and route off-set, and direct-to heading advisors for non-FMS equipped aircraft. To illustrate the difference in approach between DA and FAST, we will review the recent field test conducted at the Denver Center.

DA Field Test, September 1994

The objectives of the field test were to evaluate the ability of CTAS to accurately predict the trajectories resulting from DA advisories, to evaluate the benefits derivable from on-board FMS capabilities, and to develop compatible air/ground procedures (ref. 15).

The test involved 97 United Air Lines flights into Denver and 26 runs using the Langley Research Center's Terminal Systems Research Vehicle (TSRV) aircraft. The United flights were included to test the robustness of the system to different aircraft types, different wind conditions, different crews, and different levels of flight management equipment. The TSRV was included to provide detailed information on the winds, and to assess the accuracy and sources of errors in the trajectory prediction algorithms. The tests were conducted with airspeeds varying between 240 and 320 KIAS. Participating United Airlines flights included B757 and B737 aircraft equipped with flight management systems and B727 and B737 without flight management systems. The TSRV was flown as a conventionally equipped aircraft and an FMS equipped aircraft.

The test was configured to negate the impact on air traffic or air carrier operations. The configuration is shown in figure 13. A DA test station was set up in the Traffic Management Unit of the Denver en-route center. The existing CTAS system that supports TMA at Denver was used. The DA advisories were transmitted to a test engineer located at the sector controller position. The test engineer passed the advisory to the sector controller in a written script. The sector controller then issued the advisory to the participating flight.

An example of a DA advisory for an unequipped aircraft would be:

> "UAL 123, begin descent 70 miles from the Meeker VORTAC; descend at 280 knots; if unable advise."

An example DA advisory for a FMS equipped aircraft would be:

> "UAL 123, descend at pilot's discretion, descend at 280 knots; if unable advise."

The exact phraseology and procedures were carefully coordinated between the facility and United Airlines.

Examples of the data collected are shown in figure 14. Both horizontal and vertical profile data as well as ETA errors were recorded. The data shown are for an aircraft with an FMS and for an aircraft without an FMS. A summary of the accuracy achieved at the meter fix is shown in table 1 in the form of mean and root mean square (rms). In all cases the CTAS prediction was within 20 seconds. The FMS in the TSRV predicted crossing time is also shown for comparison.

It should be noted that these data are based on a single DA clearance and a prediction approximately 15 minutes before the meter-fix crossing.

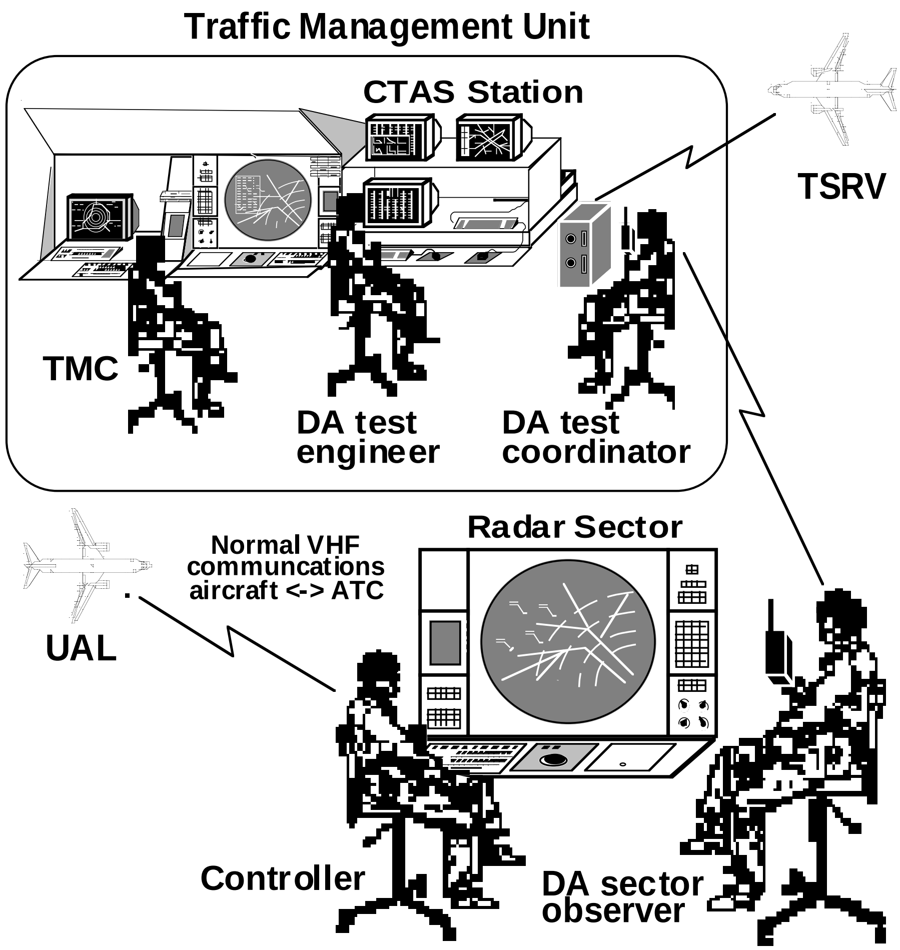


Figure 13. DA test configuration.

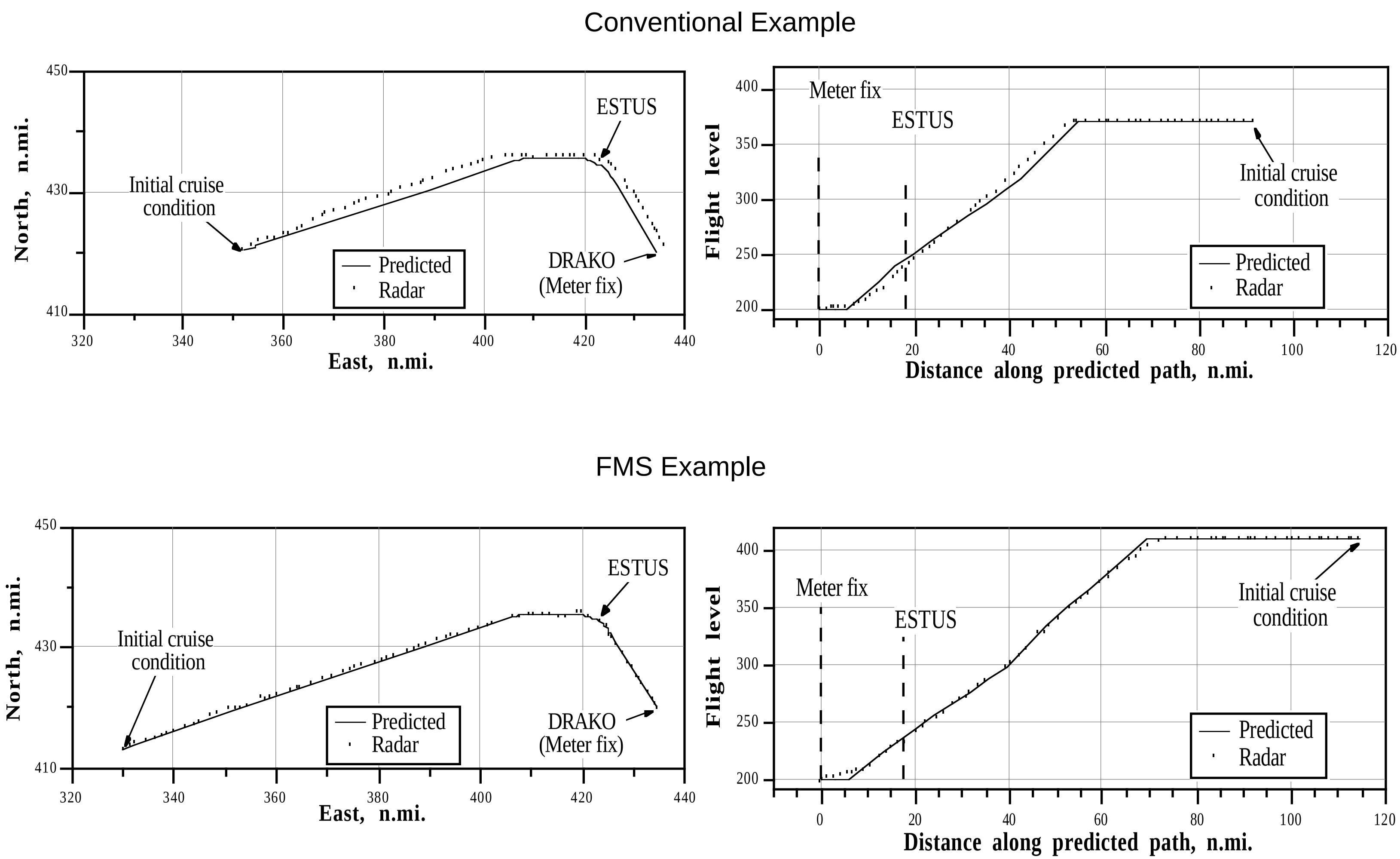


Figure 14. Trajectory data collection.

Table 1. Meter fix crossing time accuracy (seconds)

Guidance mode	TSRV aircraft FMS prediction	TSRV aircraft CTAS prediction	UAL aircraft CTAS prediction
All	8.8 mean, 10.5 rms	–2.3 mean, 12.5 rms	2.4 mean, 13.1 rms
non-FMS	16.8 mean, 9.4 rms	1.7 mean, 10.0 rms	7.4 mean, 14.3 rms
FMS	4.9 mean, 9.4 rms	–6.3 mean, 12.4 rms	–2.5 mean, 10.0 rms

As previously noted, fast time analysis has indicated a strong relation between operational benefits and the accuracy with which aircraft are delivered across the meter-fix. Based on a preliminary extrapolation of this analysis, the better than 20 second delivery accuracy shown above to be achievable with DA, together with the benefits derivable with FAST and TMA are estimated to be in the order of $33M per year at the DFW airport. These data are being used by the FAA to develop a comprehensive assessment of the benefits achievable with CTAS.

Concluding Remarks

Because of the complexity of air traffic control, CTAS has been developed using a “design a little, test a lot” philosophy. Controllers and the piloting community have been involved in the design throughout the program. In the case of FAST, most operational issues could be adequately addressed through a combination of real-time simulation and shadow-mode testing. Operational tests are scheduled to begin this fall to validate the concept in real operations in anticipation of national deployment. In the case of DA, the total system performance is highly dependent on the compatibility between aircraft or pilot and controller procedures. Issues that will affect system performance include the adequacy of the aircraft and wind modeling, and the ability and willingness of the crew to follow DA advisories. This difference has led to a greater involvement by pilots throughout the design and the initiation of early and non-intrusive field evaluations.

Fast-time simulations and analysis of real-time data are used to quantify the performance of the system and to provide a basis for extrapolating limited results from real-time simulation, shadow-mode testing, and limited field tests to a variety of cases in a statistically significant manner.

Results to date indicate a tremendous operational benefit through the introduction of CTAS type automation tools.

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